

# Magnetic entropy change associated with critical behavior in the precursor region of single crystalline FeGe

Lisha Xu,<sup>1</sup> Hui Han,<sup>2</sup> Jiyu Fan,<sup>1,\*</sup> Haifeng Du,<sup>2</sup> Lei Zhang,<sup>2,†</sup> Dazhi Hu,<sup>1</sup>  
Yandan Ji,<sup>1</sup> Jindong Liu,<sup>1</sup> Daning Shi,<sup>1</sup> Yuheng Zhang,<sup>2</sup> and Hao Yang<sup>1,‡</sup>

<sup>1</sup>*Department of Applied Physics, Nanjing University of  
Aeronautics and Astronautics, Nanjing 210016, China*

<sup>2</sup>*High Magnetic Field Laboratory, Chinese Academy of Sciences, Hefei 230031, China*

(Dated: September 22, 2016)

## Abstract

Cubic helimagnet FeGe has emerged as a class of skyrmion materials near room temperature that may impact future information technology. Experimentally identifying the detailed properties of skyrmion materials enables their practical application acceleratedly. Here we study the magnetic entropy change (MEC) of single crystalline FeGe in its precursor region and clarify its close relation to the critical exponents of a second-order phase transition in this area. The maximum MEC is found to be 2.86 J/kg.K for 7.0 T magnetic field change smaller than that of common magnetocaloric materials indicating the multiplicity and complexity of the magnetic structure phases in the precursor region. This result also implies that the competition among the multimagnetic phases can partly counteract the magnetic field driven force and establishes a stable balance. Based on the obtained MEC and the critical exponents, the exact Curie temperature of single crystalline FeGe under zero magnetic field is confirmed to be 279.1 K, higher than previously reported 278.2 K. This finding pave the way for reconstruction of FeGe phase diagram in the precursor region.

PACS numbers: 75.30.Kz, 75.30.Sg, 75.70.Kw

---

\*Electronic address: [jiyufan@nuaa.edu.cn](mailto:jiyufan@nuaa.edu.cn)

†Electronic address: [zhanglei@hmfl.ac.cn](mailto:zhanglei@hmfl.ac.cn)

‡Electronic address: [yanghao@nuaa.edu.cn](mailto:yanghao@nuaa.edu.cn)

## I. INTRODUCTION

Novel magnetic materials exhibit a plethora of fascinating features and aspects rendering them relevant for basic research as well as for potential applications. Recently, magnetic skyrmions, a topologically nontrivial vortex-like magnetic structure, are promising for building next-generation magnetic memories and spintronic devices due to their stability, small size and the extremely low currents needed to move them[1, 2]. In particular, skyrmion-based racetrack memory is attractive for information technology, where skyrmions are used to store information as data bits instead of traditional domain walls. Most of magnetic skyrmions have been found in chiral-lattice magnets, e.g., MnSi with B20-type crystal structure[3]. Due to the lack of inversion symmetry, Dzyaloshinskii-Moriya (DM) interaction shows up in competition with the ferromagnetic interaction, resulting in the helical (screw) spin structure at zero magnetic field as well as in the conical and skyrmion lattice structures in moderate magnetic fields. Besides MnSi, observations of such chiral skyrmions have been also reported in noncentrosymmetric cubic ferromagnets (Fe,Co)Si and  $\text{Cu}_2\text{OSeO}_3$  and in monolayers of Fe with a strong surface induced DM coupling[4–7]. Moreover, the skyrmions crystal has been also recently reported in centrosymmetric cubic perovskite manganites  $\text{La}_{2-2x}\text{Sr}_{1-2x}\text{Mn}_2\text{O}_7$ [8]. However, skyrmions state were mostly observed at low temperatures and under the impact of external magnetic fields. The topological spin textures of skyrmions in  $\text{Fe}_{0.5}\text{Co}_{0.5}\text{Si}$  and MnSi show up only in a low-temperature region of  $T < 40$  K while skyrmions crystal in  $\text{La}_{2-2x}\text{Sr}_{1-2x}\text{Mn}_2\text{O}_7$  is observed at  $T = 20$  K[8, 9]. Therefore, exploration of the material possessing the room-temperature skyrmion crystal is definitely desirable for practical applications.

In 2011, skyrmions crystal near room temperature was first reported in FeGe film at 260 K by Yu et al.[10]. Up to present, there are no other reported materials having such high temperature. Therefore, FeGe becomes the most promising candidate for realizing future application of skyrmion states in spintronics. The cubic FeGe belongs to the space group  $P2_13$ , in which the non-centrosymmetric cell results in a weak DM interaction [11]. For FeGe, its skyrmion phase emerges in a narrow temperature range just below 278.2 K in the field range from 0.15 to 0.4 kOe. Besides skyrmion phase, however, more and more studies show that the most enigmatic and puzzling issue of FeGe is the existence of precursor region which comprises the so-called A-phase and a sequence of complex phase

transitions and crossovers in the vicinity of the onset of long-range magnetic order at  $T_C$ [12]. Many measurements including magnetic ac-susceptibility[13], specific heat[12], electron spin resonance[14], small-angle neutron scattering[15] have been performed on FeGe to investigate this precursor region. Nevertheless, the origin and composition of precursor region is not well understood and maintain a long-standing and intriguing problem in helimagnets.

Although the precursor region only exists below  $T_C$  within a narrow temperature region (about 5 K), it relates with the following complex phase transition and the formation of long-range magnetic order at much lower temperature. Recently, the critical behavior of paramagnetic-ferromagnetic(PM-FM) phase transition of FeGe in the vicinity of  $T_C$  has been studied[16]. The results show that the macroscopical ferromagnetism is composed of some short-range magnetic interactions and the anisotropy of magnetic exchange exists in the precursor region. Therefore, the accurate determination of phase transition temperature ( $T_C$ ) will help us to further understand the composition of precursor region and reconstruct the more clear phase diagram. Considering the sharp PM-FM transition near  $T_C$  in precursor region, in this paper, our main objective is to explore the accurate phase transition temperature under zero magnetic field through analyzing the relationship between the critical exponents and magnetic entropy change(MEC), which allows considerable insight into the beginning part of precursor region and the nature of a multiplicity of magnetic phases within this area. The present studies show the maximum value of MEC is 2.86 J/kg.K as the magnetic field reaches  $\mu_0 H=7.0$  T, implying that the coexistence and competition between exchange anisotropy and magneto-crystalline anisotropy can form a stable balance which is not apt to change with applying magnetic field. Moreover, this result also identified the earlier findings that the strong competition among the multi-magnetic interactions could soften the magnetization in the precursor region although FeGe has a sharp PM-FM phase transition at  $T_C$ . Meanwhile, a new method that depends on the critical exponents and the MEC under the different magnetic fields was applied to confirm the central position of the precursor region. The exact Curie temperature is 279.1 K rather than 282 K obtained from temperature dependent on magnetic susceptibility of the present single crystalline and 278.2 K in the previous report[13].

## II. EXPERIMENT

A single crystalline B20-type FeGe was synthesized with high-pressure apparatus.[17] The magnetization was measured using a Quantum Design vibrating sample magnetometer (SQUID-VSM) and the no-overshoot mode was applied to ensure a precise magnetic field. The applied field was relaxed for 2 min before the data collection. To make sure that each curve was initially magnetized, the isothermal magnetization measurement was performed after the sample was heated well above  $T_C$  for 10 min and then cooled under zero field to the target temperatures.

## III. RESULTS AND DISCUSSION

Figure 1(a) shows the temperature dependence of magnetic susceptibility ( $\chi$ -T) of single crystalline FeGe, which is measured on the warming process after zero field cooling and field cooling under magnetic field of 100 Oe. A sharp PM-FM phase transition occurs around  $T_C=282$  K (The Curie temperatures( $T_C$ ) can be determined from the peak of  $d\chi/dT$  (inset of Fig. 1(a))). The right axis of Fig. 1(a) presents the reciprocal magnetic susceptibility vs. temperatures and the solid line is the fitting results by using the Curie-Weiss Law  $\chi=C/(T-T_{CW})$  ( $C$  is the Curie constant and  $T_{CW}$  is the Curie-Weiss temperature). Clearly, the relationship between  $\chi^{-1}$  and  $T$  preferably follows the Curie-Weiss Law and the fitting  $T_{CW}=283$  K is also basically agreement with the Curie temperature 282 K. Meanwhile, the effective PM moment( $P_{eff}=2.82\sqrt{C}=2.533\mu_B$ ) can be also calculated from the fitting Curie constant  $C$ .

Figure 1(b) shows the isothermal M-H curve measured at 4.0 K. With the increase of the applied magnetic field, the magnetization increases sharply, and then tends to saturation as  $\mu_0H=0.5$  T. The saturated magnetization ( $M_S=0.961\mu_B$ ) can be obtained from an extrapolation of the high field M-H curve to  $\mu_0H=0$ . According to Rhodes- Wohlfarth criterion[20], the degree of itinerancy can be determined from the ratio of  $P_{eff}$  to  $M_S$ . The ratio is close to one for the localized moment whereas it is larger than one for the itinerant moment. Here, the ratio of 2.63 implies that the electrons possess an itinerant characteristic in FeGe sample. As we know, the interaction between spin, orbital, charge, and lattice of freedom would be suppressed in a ferromagnet, hence the properties of magnetic phase transition can

be clarified with macroscopic magnetization. The inset of Fig. 1(b) presents the isothermal magnetization vs magnetic field around 282 K. Depended on it, the properties of phase transition of precursor region can be uncovered. Recently, the critical behavior of bulk FeGe has been investigated through the isothermal M-H curves and the obtained results indicate that the magnetic interaction of FeGe belongs to a short-range magnetic coupling in precursor region[16].

From the Maxwell relations based on the thermodynamical theory, the magnetic entropy change, induced by changing the magnetic field from 0 to  $\mu_0 H$ , can be evaluated from the temperature using a numerical approximation as follows:  $\Delta S_M(\mu_0 H, T) = S_M(\mu_0 H, T) - S_M(0, T) = \int_0^{\mu_0 H_{max}} (\frac{\partial M(\mu_0 H, T)}{\partial T}) d(\mu_0 H)$ , where  $\mu_0 H$  is the magnetic field, T is the temperature and  $\mu_0 H_{max}$  is the maximum of the magnetic field. In the case of magnetization measurements at small discrete magnetic field and temperature intervals,  $\Delta S_M$  can be approximated as:  $\Delta S_M(\frac{T_1+T_2}{2}) = \frac{1}{T_1-T_2} [\int_0^{\mu_0 H_{max}} M(T_2, \mu_0 H) d(\mu_0 H) - \int_0^{\mu_0 H_{max}} M(T_1, \mu_0 H) d(\mu_0 H)]$ . According to this formula, the MEC for FeGe can be calculated by utilization of isothermal magnetization in Fig. 1(b) and the obtained  $\Delta S$  is given in Fig. 2(a). The  $\Delta S_M$  shows a maximum value near 282 K and it decreases symmetrically on both sides. The magnitude of  $\Delta S_M$  increases with the rise of applying magnetic field and reaches a maximum value of 2.86 J/kg.K for  $\mu_0 H=7.0$  T. Obviously, compared to those of well-known magnetocaloric standards, the values of  $\Delta S_M$  remains relatively small. In the earlier investigations on FeGe, some special anomalies around  $T_C$  such as U-like transition of AC susceptibility and  $\lambda$ -like variation of specific-heat transition have been found[13, 18]. Different from the general magnetic materials, cubic helimagnet FeGe does not promptly form a long-range ordering magnetic structures at  $T \leq T_C$ . On the contrary, at the range of  $\sim 5$  K below  $T_C$ , there are at least 2-3 segmented magnetic phase embedded in the conical phase[12]. The experimental results reveal that these magnetic structure phases are not only temperature-dependent but also magnetic field-dependent[13]. Therefore, the phase diagram in this temperature region is very complex. Moreover, at the range of  $\sim 5$  K above  $T_C$ , the sample does not also show a pure PM state. Recent thermodynamic investigations show a remarkable anomaly of a sharp peak occurred at the temperature slightly above  $T_C$ [18], implying that the magnetic component in this temperature range may be a intermediate state instead of a single PM or a helical phase. Therefore, in precursor region, the applied magnetic field being a sole driving force is impossible to make the coexistence of a multi-magnetic phases to become an

ordering magnetic structure. According to the classical Boltzmann relation  $S=k_B \ln \Omega$ , here, because the systemic disordering degree  $\Omega$  does not significantly reduce under external magnetic field, the MEC is naturally unable to achieve a large variation. It agrees reasonably well with the small value of MEC obtained in present FeGe.

Nevertheless, note that Fig. 2(a) shows a broad variation of  $\Delta S_M$  with temperatures around  $T_C$ . Such a variation covering a broad temperature range maybe beneficial for magnetic cooling application in some special fields. One of important parameters used to estimate the magnetic cooling application is the change of specific heat ( $\Delta C_p$ ). The specific heat can be calculated from the magnetic contribution to the entropy change induced in FeGe by the following expression:  $\Delta C_p(T, \mu_0 H) = C_p(T, \mu_0 H) - C_p(T, 0) = T \frac{\partial \Delta S_M(T, \mu_0 H)}{\partial T}$ . Fig. 2(b) shows the  $\Delta C_p$  vs temperature under different variations of the applied magnetic field calculated from the  $\Delta S_M$  data (Fig. 2(a)). One can see that the  $\Delta C_p$  changes suddenly around  $T_C$  from positive to negative value with a positive value above  $T_C$  but a negative value below  $T_C$ . The sum of the two parts is the magnetic contribution to the total specific heat which affects the cooling or heating power of the magnetic refrigerator. Beside, the maximum/minimum values of  $\Delta C_p$  exhibit an increasing trend with the applied magnetic field, and are observed at the temperatures 280/290 K in 7.0 T.

Generally, the order of magnetic phase transition can be distinguished by the criterion suggested by Banerjee[19]. Negative and positive slope of  $H/M$  vs  $M^2$  curves respectively correspond to a first-order and second-order transition. However, Franco et al. recently proposed a phenomenological universal curve which could be more accurate to judge the order of magnetic phase transition. It is constructed by normalizing all the  $\Delta S_M$  curves against their respective maximum  $\Delta S_M^{max}$ [20, 21], namely,  $\Delta S'_M = \Delta S_M / \Delta S_M^{max}$  with rescaling the temperature axis ( $\theta$ ) below and above  $T_C$  as defined in Eq. 1

$$\theta = \begin{cases} \theta_- = (T_{peak} - T) / (T_{r1} - T_{peak}), & T < T_{peak} \\ \theta_+ = (T - T_{peak}) / (T_{r2} - T_{peak}), & T > T_{peak} \end{cases} \quad (1)$$

where  $T_{r1}$  and  $T_{r2}$  are the temperatures of the two reference points that have been selected as those corresponding to  $\Delta S_M(T_{r1}, T_{r2}) = \frac{1}{2} \Delta S_M^{max}$ . As shown in Fig. 2(c), all the  $\Delta S_M$  vs.  $T$  curves under different magnetic fields collapse into a single curve further confirming a second order phase transition for FeGe. In precursor region, the presence of small hysteresis in a magnetic cycle and multi-peaks in isothermal susceptibility have been found[12, 18],

indicating that the transition between the helical, conical, and the A-phase is of first-order in nature. Despite all this, these mutual transitions only occur in low field region ( $H < 0.1$  T). As the applied magnetic field is far more than 0.1 T, these first-order transitions were driven to a second-order. In the present study, the maximum magnetic field was applied up to 7.0 T. Therefore, only a second-order PM-FM phase transition was observed. Its properties can be characterized by some interrelated critical exponents,  $\beta$  (associated with the spontaneous magnetization  $M_s$ ),  $\gamma$  (associated with the initial magnetic susceptibility  $\chi_0$ ),  $\delta$  (associated with the critical magnetization isotherm at  $T_C$ ). For the observed PM-FM phase transition of Fig. 1(a), these critical exponents ( $\beta=0.336$ ,  $\gamma=1.352$ ,  $\delta=5.276$ ) have been obtained by numerical calculation method[16]. Here, we can further check the veracity of the critical exponents and disclose their relationship between magnetic entropy change and critical exponents. In phase transition region,  $\Delta S_M$  can be scaled by the scaled equation of state ( $\frac{\mu_0 H}{M^\delta} = f[\frac{\epsilon}{M^{1/\beta}}]$ )[22, 23] and the  $\Delta S_M$  can be rewritten into another format:

$$\Delta S_M(\mu_0 H, T) = (\mu_0 H)^{1-\alpha/\Delta} g\left(\frac{\epsilon}{(\mu_0 H)^{1/\Delta}}\right) \quad (2)$$

Where  $\alpha$  and  $\Delta$  are two critical exponents ( $\alpha=2-2\beta-\gamma$  and  $\Delta=\beta+\gamma$ ),  $\epsilon$  is the reduced temperature ( $\epsilon=\frac{T-T_C}{T_C}$ ). If the critical exponents are appropriately chosen, the  $\Delta S_M$  vs.  $T$  curves should be also rescaled into a master curve, consistent with normalizing all the  $\Delta S_M$  curves with two reference temperatures ( $T_{r1}$  and  $T_{r2}$ ). Together with the obtained critical exponents, the  $\Delta S_M$  vs  $T$  curves under variational magnetic fields in Fig. 2(a) were re-plotted as  $\frac{-\Delta S_M(\mu_0 H, T)}{(\mu_0 H)^{1-\alpha/\Delta}}$  vs  $\frac{\epsilon}{(\mu_0 H)^{1/\Delta}}$  curves. As shown in Fig. 2(d), one can find that all the MEC collapse on a single curve for different temperature and magnetic field. This excellent overlap clearly indicates that the obtained critical exponents of  $\beta$  and  $\gamma$  for FeGe sample are not only in agreement with the scaling hypothesis but also very reliable.

In the following section, we will clarify the influence of critical exponents on MEC. Fig. 3(a) presents the magnetic field dependence of isothermal entropy change at the individual temperatures. Obviously, in Fig. 3(a), all the entropy changes reveal a monotonic increase with the applied magnetic field at different temperatures. In general, it can be assumed that the field dependence of the magnetic entropy follows a power law expressed as  $\Delta S_{max} \approx a(\mu_0 H)^n$ [24, 25], where “a” is a constant and the exponent “n” is an exponent related to magnetic order and depends on temperature and magnetic field as follows:

$$n(T, \mu_0 H) = \frac{d \ln(|\Delta S_m|)}{d \ln(\mu_0 H)} \quad (3)$$

For the ferromagnet undergoing a second-order phase transition,  $n$  tends to 1 and is magnetic-field independent at temperatures  $T \ll T_C$  but it tends to 2 at temperatures  $T \gg T_C$  and reaches to a minimum value equal to  $2/3$  at  $T_C$ [26]. As shown in Fig. 3(b), it can be found that the value of  $n$  is around 1.0 and reaches 1.9 far below and above  $T_C$ , respectively, basically consistent with the universal law of  $n$ -change[27, 28]. At  $T \sim 282$  K, except the value of  $n(\mu_0 H = 1.0 \text{ T}) = 0.702$ , other values almost concentrate around 0.665, very close to the theoretical data of  $2/3$  at  $T_C$ . Here, we can also further check the validity of the obtained critical exponents of  $\beta$  and  $\gamma$  for FeGe. In fact, at  $T = T_C$ , the value of  $n$  should strictly obey this variation established as  $n(T_C) = 1 + \frac{\beta-1}{\beta+\gamma}$  [29]. With  $\beta = 0.336$  and  $\gamma = 1.352$ , the calculated value of  $n = 0.61$  was completely consistent with  $n(\mu_0 H = 7.0 \text{ T}) = 0.607$  of Fig. 3(b).

Besides that the value of  $n(T, \mu_0 H)$  can reflect the relationship between critical exponents and MEC, the Curie temperature can be also deduced from it. In present, the main method to determinate the Curie temperature is generally based on the differential data of  $M(T)$  curve or the linear fitting of the inverse magnetic susceptibility vs. temperatures curves. However, in order to increase signal to noise ratio. the actual measurement of magnetization always is carried out with applying a certain magnetic field. Thus, the obtained Curie temperature is necessarily magnetic field dependent rather than independent. Recently, a new method was suggested to deduce the Curie temperature that is not only more accurate but also magnetic field independent[30]. Combining Eq. 3 and the partial differential formation of Eq. 2, the value “ $n$ ” can be scaled as:

$$n = \frac{1 - \alpha}{\Delta} - \frac{1}{\Delta} \left( \frac{\partial \ln g(\frac{\epsilon}{H^{1/\Delta}})}{\partial \ln(\frac{\epsilon}{H^{1/\Delta}})} \right) \quad (4)$$

Obviously, as  $T = T_C$ ,  $\frac{\epsilon}{H^{1/\Delta}} = 0$  and  $n = \frac{1-\alpha}{\Delta}$ ; on the other hand, as  $\Delta S(T = T_{peak}) = \Delta S_{max}$ ,  $\frac{\partial \ln g(\frac{\epsilon}{H^{1/\Delta}})}{\partial \ln(\frac{\epsilon}{H^{1/\Delta}})} = 0$  and  $n = \frac{1-\alpha}{\Delta}$ . So, the second term of Eq. 4 vanishes at both  $T = T_{peak}$  and  $T = T_C$  and the value of  $n(T = T_{peak})$  is equal to  $n(T = T_C)$ . Thus, the accurate Curie temperature  $T_C$  can be deduced from a linear interpolation of  $n(T, \mu_0 H)$  curve. Here, we choose three representative magnetic fields ( $\mu_0 H = 1.0, 3.0, 6.0 \text{ T}$ ) to deduce the Curie temperature  $T_C$ . As shown in Fig. 4(a,b,c), the Curie temperature  $T_C$  is about 278.7, 279.2, and 279.3

K, respectively. Fig. 4(d) shows all deduced Curie temperatures under seven different magnetic fields. If we adopt arithmetic mean value to determinate the Curie temperatures, the accurate  $T_C$  should be 279.1 K shown as the dotted line in Fig. 4(d). There is a discrepancy of 2.9 K comparing with  $T_C=282$  K determined from Fig. 1(a).

In order to identify the reliability of  $T_C=279.1$  K, we can check it from the magnetic field dependent refrigerant capacity power (RCP) which represents the heat to be transferred from the cold end ( $T_{cold}$ ) to the hot end ( $T_{hot}$ ) of the refrigerator in one thermodynamic cycle. RCP can be calculated by integrating the  $(\Delta S_M - T)$  curves over the full width at half maximum using the relation  $RCP = \int_{T_{cold}}^{T_{hot}} \Delta S_M dT$ . As shown in Fig. 5(a), the obtained RCP values increase with the applied magnetic field indicating that RCP is strong field dependent. RCP depends on magnetic field  $H$  with the rule  $RCP = aH^b$ . By using it, as shown in inset of Fig. 5(a), the value of  $b=1.206$  was obtained. In fact, the value of  $b$  is also related to the critical exponent  $\delta$  ( $b=1+\frac{1}{\delta}$ , where  $\delta$  is associated with the critical magnetization isotherm at  $T_C$  ( $M_{T=T_C} \propto H^{1/\delta}$ )). So, based on the RCP results in Fig. 5(a), the critical exponent  $\delta=4.854$  for single crystalline FeGe can be obtained. On the other hand, the value of  $\delta$  can be also directly deduced from the isothermal magnetization curves at  $T_C$ . Thus, under the premise of unknown exact Curie temperature, we can choose some possible isothermal magnetization curves which temperatures are close to exact Curie temperature to deduce the corresponding  $\delta$ . Then, we can compare these data with  $\delta=4.854$  deduced from RCP. Which discrepancy is the least, which temperature is the Curie temperature. Here, we choose three most possible temperatures ( $T=278, 279, 280$  K) to deduce the value of  $\delta$ . As shown in the insets of Fig. 5(b, c, d), the values of  $\delta$  are 4.895, 4.645, and 5.136 for  $T=279, 280$ , and  $278$  K, respectively. Obviously, the value of 4.895 at 279 K is closest to the  $\delta=4.854$ . Therefore,  $T=279$  K can be referred to the Curie temperature instead of 282 K previously determined from the derivative magnetic susceptibility, which also agrees well with the deduced  $T_C=279.1$  K in this work.

The earliest investigation about the Curie temperature of FeGe was first performed by Lundgren et al. and it was estimated to be  $T_C=280 \pm 2$  K[31]. Whereafter, the Curie temperature was reported to be  $T_C=278.2$  K by Wilhelm et al. from the measurement of AC magnetic susceptibility[13], lower than 279.1 K determined in the present sample. However, the temperature of  $T_C=279.1$  K is very close to their reported 279.6 K where the specific heat results show a noticeable anomaly under zero magnetic field[12]. They proposed

that the appearance of anomaly on specific heat prior to the long-ranged FM order setting in at  $T_C$  implied the formation of magnetic order phase above  $T_C$  due to spin fluctuations. For FeGe, nevertheless, the spin fluctuations are unobvious as the Fe ions possess a stable magnetic moment[32]. Considering the fact that both 279.1 and 279.6 K are obtained under the condition of zero magnetic field, we think the abnormal magnetic order emerged might be not obvious above  $T_C$ . Recently, the detailed isothermal susceptibility results also indicate that the curve shapes at 279.5 and 279 K are almost the same whereas the curve at 278.5 K starts to show a double-peaks structures[18]. Therefore, the start location of the precursor region can be considered at 279.1 K and the phase boundary of phase diagram need to be adjusted accordingly.

#### IV. CONCLUSION

In summary, we have studied in detail the magnetic and MEC for Helimagnet FeGe. A second-order transition from PM to FM phase around  $T_C$  has been confirmed by the scaling MEC. A relative small MEC obtained in this sample indicates that the coexistence and competition between exchange anisotropy and magneto-crystalline anisotropy can form a stable balance in the precursor region while the applied magnetic field is unable to completely transform it into a single magnetic structure phase. Moreover, a more precise method for determining the Curie temperature was carried on FeGe sample. We found the actual Curie temperature of it should be 279.1 K rather than 282 K deduced directly from the derivative magnetic susceptibility.

#### V. ACKNOWLEDGMENT

This work was supported by the National Nature Science Foundation of China (Grant Nos. 11274327, 11374159, 11574322, U1632122, and U1332140) and the Foundation for Users with Potential of Hefei Science Center (CAS) through Grant No. 2015HSC-UP001.

---

[1] N. Nagaosa and Y. Tokura, Nat. Nanotechnol. **8**, (2013) 899.

- [2] A. Fert, V. Cros, and J. Sampaio,, Nat. Nanotechnol. **8**, (2013) 152.
- [3] S. Mühlbauer, B. Binz, F. Jonietz, C. Pfleiderer, A. Rosch, A. Neubauer, R. Georgii, and P. Böni, Science **323**, (2009) 915.
- [4] X. Z. Yu, Y. Onose, N. Kanazawa, J. H. Park, J. H. Han, Y. Matsui, N. Nagaosa, and Y. Tokura, Nature (London) **465**, (2010) 901.
- [5] T. Adams, A. Chacon, M. Wagner, A. Bauer, G. Brandl, B. Pedersen, H. Berger, P. Lemmens, and C. Pfleiderer, Phys. Rev. Lett. **108**, (2012) 2372047.
- [6] A. Sonntag, J. Hermenau, S. Krause, R. Wiesendanger, Phys. Rev. Lett. **113**, (2014) 077202.
- [7] E. Simon, K. Palotas, L. Rozsa, L. Udvardi, L. Szunyogh, Phys. Rev. B **90**, (2014) 094410.
- [8] X. Z. Yu, Y. Tokunaga, Y. Kaneko, W. Z. Zhang, K. Kimoto, Y. Matsui, Y. Taguch, and Y. Tokura, Nat. Commun. **5**, (2014) 3198.
- [9] A. Neubauer, C. Pfleiderer, B. Binz, A. Rosch, R. Ritz, P. G. Niklowitz, and P. Böni, Phys. Rev. Lett. **113**, (2014) 077202.
- [10] X. Z. Yu, N. Kanazawa, Y. Onose, K. Kimoto, W. Z. Zhang, S. Ishiwata, Y. Matsui, and Y. Tokura, Nat. Mater. **102**, (2009) 186602.
- [11] B. Lebech, J. Bernhard, and T. Freiltoft, J. Phys. Condens. Matter **1**, (1989) 6105.
- [12] H. Wilhelm, M. Baenitz, M. Schmidt, C. Naylor, R. Lortz, U. K. Rößler, A. A. Leonov, and A. N. Bogdanov, J. Phys. Condens. Matter **24**, (2012) 294204.
- [13] H. Wilhelm, M. Baenitz, M. Schmidt, U. K. Rößler, A. A. Leonov, and A. N. Bogdanov, Phys. Rev. Lett. **107**, (2011) 127203.

- [14] J. Sichelschmidt, M. Schmidt, H. Wilhelm, and U. K. Rößler, J. Phys.: Conf. Ser. **391**, (2012) 012105.
- [15] U. K. Rößler, A. N. Bogdanov, and C. Pfleiderer, Nature **442**, (2006) 797.
- [16] Lei Zhang, Hui Han, Min Ge, Haifeng Du, Chiming Jin, Wensen Wei, Jiyu Fan, Changjin Zhang, Li Pi, and Yuheng Zhang, Sci. Rep. **6**, (2016) 22397.
- [17] Xuebing Zhao, Chiming Jin, Chao Wang, Haifeng Du, Jiadong Zang, Mingliang Tian, Renchao Che, and Yuheng Zhang, Proc. Natl. Acad. Sci. **113**, (2016) 4918.
- [18] L. Cevey, H. Wilhelm, M. Schmidt, and R. Lortz, Phys. Status Solidi B **250**, (2013) 650.
- [19] S. K. Banerjee, Phys. Lett. **12**, (1964) 16.
- [20] C. M. Bonilla, J. Herrero-Albillos, F. Bartolome, L. M. Garcia, M. Parra-Borderias, and V. Franco, Phys. Rev. B **81**, (2010) 224424.
- [21] V. Franco, J. S. Blazquez, and A. Conde, Appl. Phys. Lett. **89**, (2006) 222512.
- [22] B. Widom, J. Chem. Phys. **43**, (1965) 3898.
- [23] R. B. Griffiths, Phys. Rev. Lett. **23**, (1969) 17.
- [24] V. Franco, J. S. Blazquez, B. Ingale, and A. Conde, Annu. Rev. Mater. Res. **42**, (2012) 305.
- [25] V. Franco, A. Conde, Int. J. Refri. **33**, (2010) 465.
- [26] H. Oesterreicher, and F. T. Parker, J. Appl. Phys. **55**, 4334 (1984).

- [27] R. Mnassi, N. Chniba-Boudjada, and A. Cheikhrouhou, J. Alloys Comp. Phys. **640**, (2015) 183.
- [28] R. Caballero-Flores, N. S. Bingham, M. H. Phan, M. A. Torija, C. Leighton, V. Franco, A. Conde, T. L. Phan, S.C. Yu, and H. Srikanth, J. Phys.: condens. Matter **26**, (2014) 286001.
- [29] V. Franco, A. Conde, J. M. Romero-Enrique, and J. S. Blazquez, J. Phys.:Condens. Matter **20**, (2008) 285207 .
- [30] L. M. Moreno-Ramírez, J. S. Blázquez, V. Franco, A. Conde, M. Marsilius, V. Budinsky, and G. Herzer, IEEE Magn. Lett. **7**, (2016) 6102004.
- [31] L. Lundgren, K. Å Blom, O. Beckman, Phys. Lett. A **28**, (1968) 175.
- [32] R. Wäppling, L. Häggström, Phys. Lett. A **28**, (1968) 173.

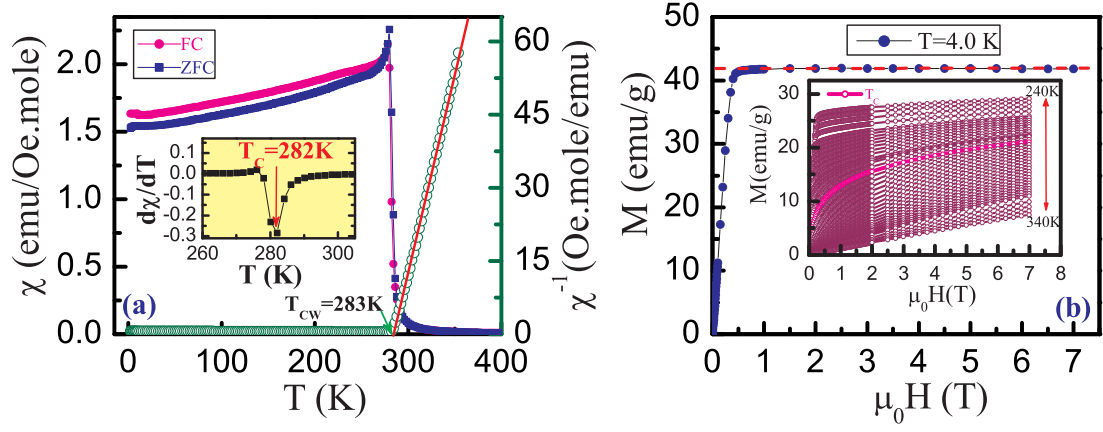


FIG. 1: (Color online)(a)Left axes: Temperature dependence of magnetic susceptibility for FeGe. Right axes: Inverse susceptibility as a function of temperature and the straight line represents the linear fitting according to the Curie-Weiss law. Inset shows the the derivative magnetic susceptibility. (b) presents the isothermal M-H curve at 4.0 K. Inset shows the isothermal M-H around  $T_C$ .

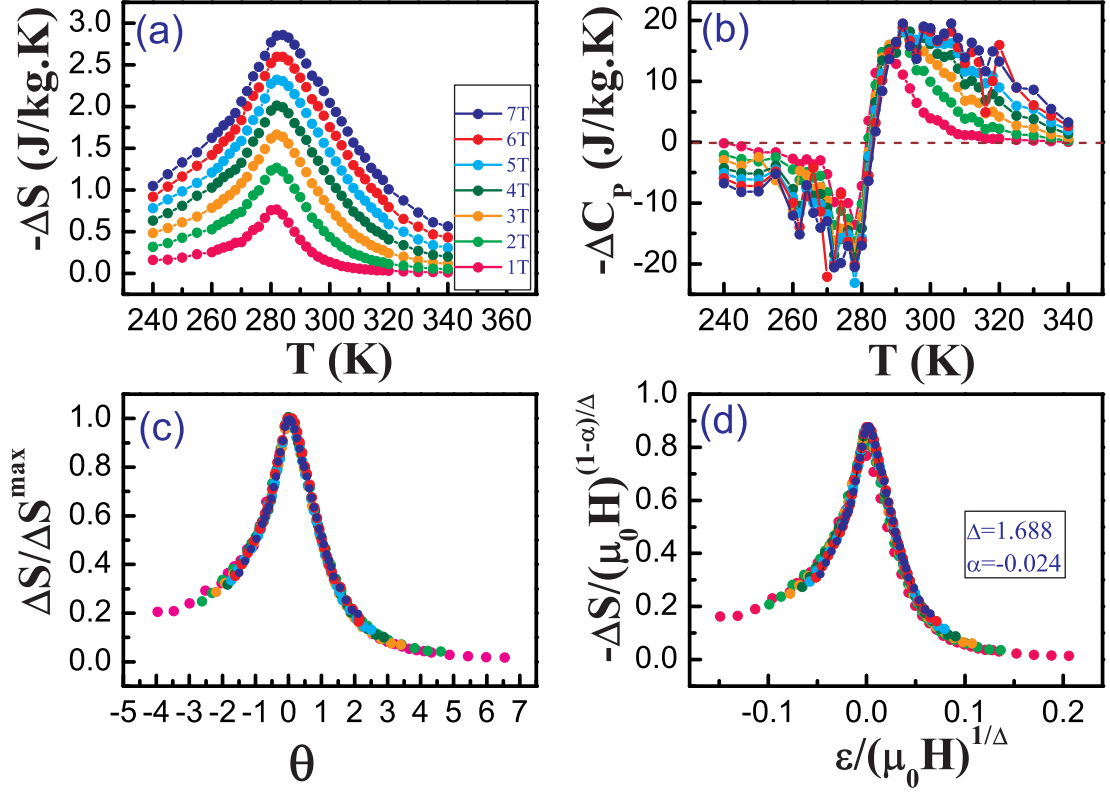


FIG. 2: (Color online)(a) Magnetic entropy change ( $-\Delta S$ ) plotted as a function of temperature( $T$ ) at different applied fields. (b) The change of specific heat  $\Delta C_P$  vs.  $T$  at different magnetic fields. (c) Normalized magnetic entropy change dependence of the rescaled temperatures. (d) The  $\Delta S$  vs.  $T$  curves under different magnetic field were replotted as  $\frac{-\Delta S_M(\mu_0 H, T)}{(\mu_0 H)^{1-\alpha/\Delta}}$  vs.  $\frac{\epsilon}{(\mu_0 H)^{1/\Delta}}$  curves.

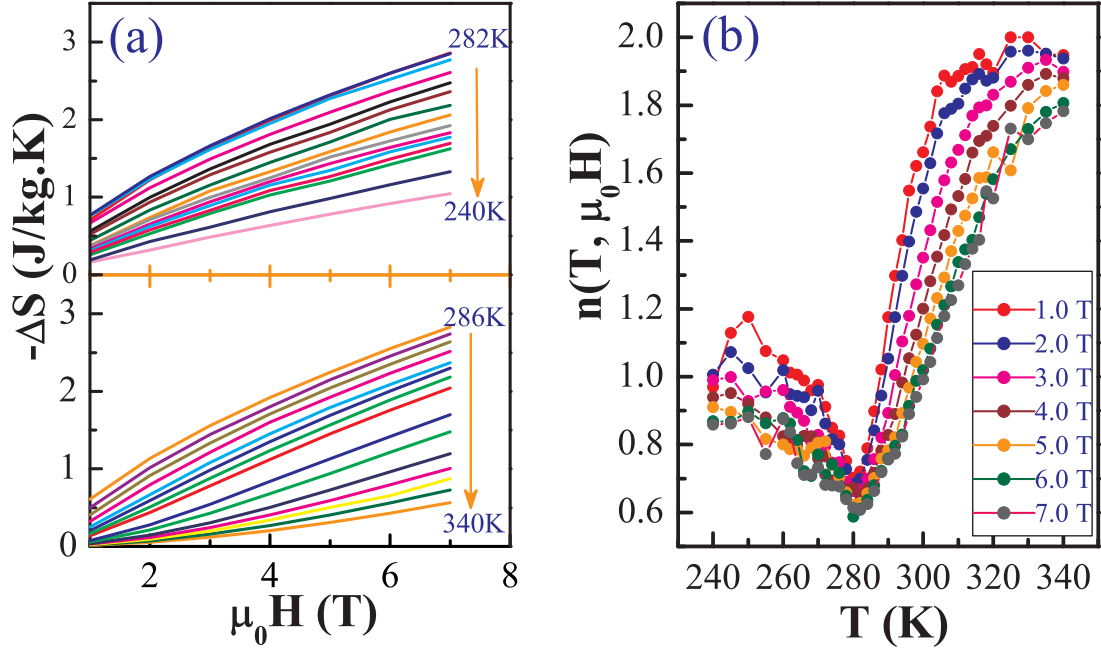


FIG. 3: (Color online)(a) The  $\Delta S$  vs.  $\mu_0 H$  at different temperatures; (b) The value of  $n$  vs.  $T$  at different external magnetic fields.

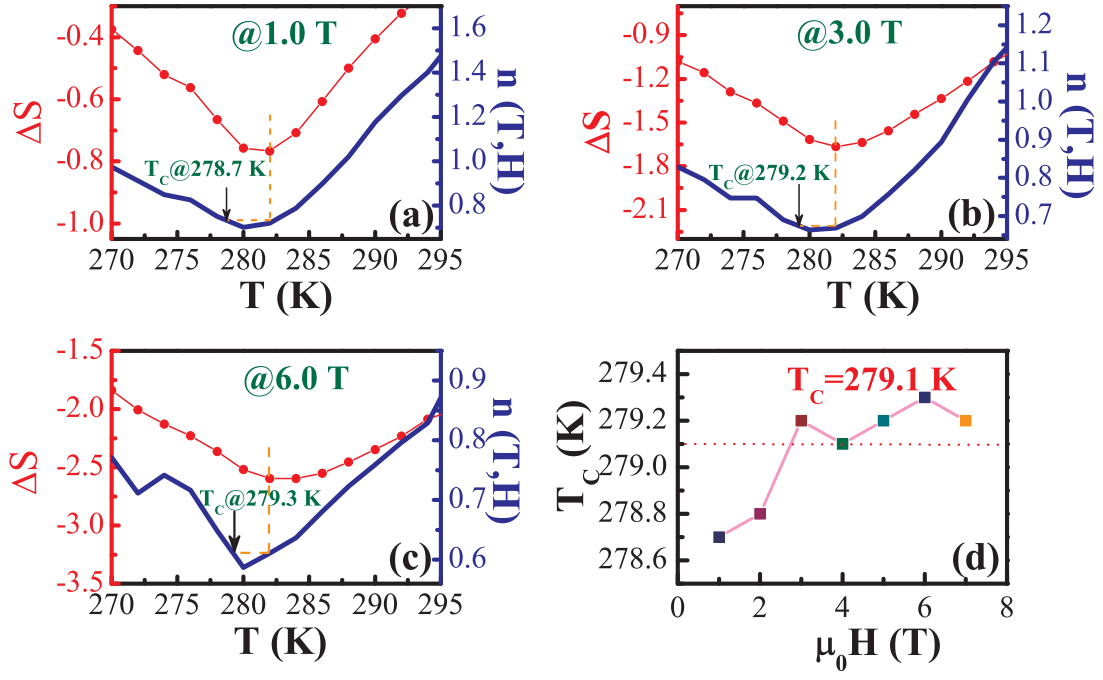


FIG. 4: (Color online) Left axes: The  $\Delta S$  vs.  $T$  for FeGe at external magnetic field of 1.0 T(a), 3.0 T(b), 6.0 T(c); Right axes: The value of  $n$  vs.  $T$  at external magnetic field of 1.0 T(a), 3.0 T(b), 6.0 T(c). (d) All the deduced Curie temperatures under different external magnetic fields and the dot line is the average Curie temperature.

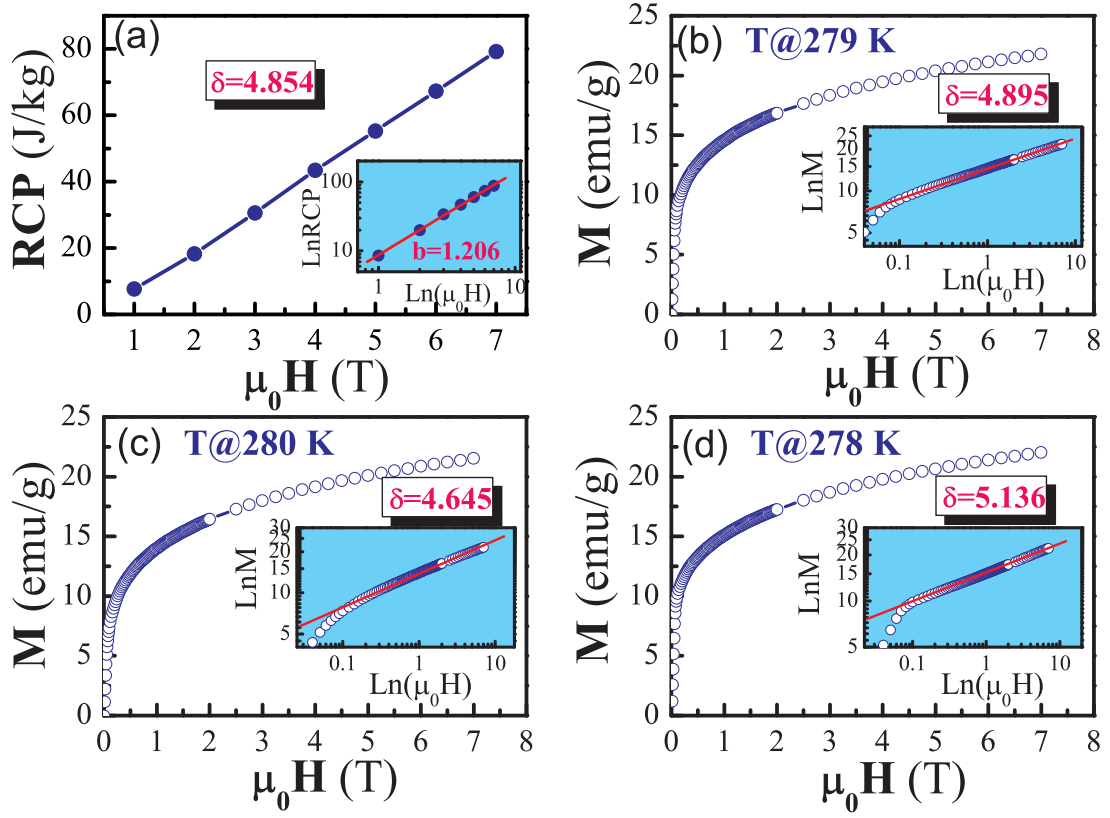


FIG. 5: (Color online)(a) Refrigerant capacity power as a function of applied magnetic field. Inset shows the same plot in log-log scale and the solid line is the fitting results following  $RCP = aH^b$ . (b, c, d) present the isothermal  $M$  vs.  $H$  plot at 279 K, 280 K and 278 K. Inset shows the same plot in log-log scale and the solid lines are the linear fitting with  $M_{TC} = DH^{1/\delta}$ .